

Prospects of Inflationary Cosmology

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Abstract

In this review I briefly describe the evolution of the inflationary theory from the scenario based on the idea of supercooling and expansion in the false vacuum toward the theory of eternally expanding self-reproducing inflationary universe. I describe recent development of inflationary cosmology with $\Omega \neq 1$, and then discuss some issues related to the possibility to verify inflation by comparing its predictions with observational data. I argue that it is possible to verify and disprove many particular models of inflationary cosmology, but it is very difficult to kill the basic idea of inflation. It seems that the best (and may be even the only) way to do so is to suggest a better cosmological theory.

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1 Various versions of inflationary cosmology

One of the highlights of the conference “Critical Dialogues in Cosmology” in Princeton was a discussion of inflationary cosmology by Alan Guth and Bill Unruh, see refs. [1] and [2] in the proceedings. Not surprisingly, I mainly agree with Alan, even though I must admit that some critical comments made by Unruh were quite appropriate. However, most of these comments were addressed to the version of inflationary theory which died almost 15 years ago. To avoid misunderstandings, one should be more specific describing inflationary cosmology.

The first semi-realistic inflationary model was proposed by Alexei Starobinsky in 1979 [3]. This model was rather complicated, it did not aim on solving homogeneity, horizon and monopole problems, but it worked. The theory of density perturbations in this model was first developed by Mukhanov and Chibisov [4], and it practically coincided with the corresponding theory developed a year later in the context of new inflation [5].

A much simpler model with a very clear physical motivation was proposed by Alan Guth in 1981 [6]. His model was so nice that even now all textbooks on astronomy and all popular books describe inflation as an exponential expansion of the universe in a supercooled false vacuum state. This is a seductively simple but incorrect way to explain the essence of inflation. Exponential expansion in the false vacuum in a certain sense is false: de Sitter space with a constant vacuum energy density equally well can be considered as expanding, contracting, or static, depending on the choice of a coordinate system. The absence of a preferable hypersurface of decay of the false vacuum was the main reason of failure of the old inflationary theory.

This problem was resolved in the new inflationary theory [7]. In this theory, just like in the Starobinsky model, inflation continues away from the false vacuum. Importance of this fact should not be overlooked: density perturbations produced during inflation are inversely proportional to $\dot{\phi}$, where ϕ is the inflaton scalar field driving inflation [4, 5]. If the field stays in the false vacuum state and does not move, one has indefinitely large density perturbations, which makes the corresponding part of inflation almost useless. Fortunately, in the new inflation scenario the field ϕ does move during inflation, which under certain conditions makes density perturbations produced during inflation relatively small.

However, new inflation was plagued by its own problems. Effective potential with a flat plateau near the origin is somewhat artificial. In most versions of the new inflation scenario the inflaton field originally could not be in a thermal equilibrium with other matter fields. The theory of high temperature symmetry restoration, which was the basis for old and new inflation, simply did not work in such a situation. Moreover, thermal equilibrium requires many particles interacting with each other. This means that new inflation could possibly explain why our universe was so large only if it was very large and contained many particles from the very beginning. Finally, inflation in this theory begins very late, and during the preceding epoch the universe could easily collapse or become so inhomogeneous that inflation may never happen. These problems have been well understood already in 1982. Unfortunately, there is a certain inertia in the development of scientific theories, and even after new inflation died there were many people who insisted that it is alive, and there were many others who did not know that it is dead and tried to criticize it. In particular, most of the critical remarks made about inflation by Bill Unruh at this conference are related to this theory.

All these problems were resolved with the introduction of the chaotic inflation scenario [8]. In this scenario inflation may occur in the theories with simplest potentials such as $\pm m^2\phi^2 + \lambda\phi^4$. It may begin even if there was no thermal equilibrium in the early universe, and it may start even at the Planckian density, in which case the problem of initial conditions for inflation can be easily resolved [8, 9]. The main idea of chaotic inflation is very simple and general. One should study all possible initial conditions without assuming that the Universe was in a state of thermal equilibrium, and that the field ϕ was in the minimum of its effective potential from the very beginning. This scenario strongly deviated from the standard lore of the hot big bang theory and was psychologically difficult to accept. Gradually, however, it became clear that the idea of chaotic initial conditions is most general, and that it is much easier to construct a consistent cosmological theory without insisting that the existence of thermal equilibrium and high temperature phase transitions in the early universe is a necessary condition for inflation to occur.

2 From the Big Bang theory to the theory of eternal inflation

The next step in the development of inflationary theory which I would like to mention here is the discovery of the process of self-reproduction of inflationary domains. This process was known to exist in old inflationary theory [6] and in the new one [10], but it is especially surprising and leads to most profound consequences in the context of the chaotic inflation scenario [11]. It appears that in many models large scalar field during inflation produces large quantum fluctuations which may locally increase the value of the scalar field in some parts of the universe. These regions expand at a greater rate than their parent domains, and quantum fluctuations inside them lead to production of new inflationary domains which expand even faster. This surprising behavior leads to an eternal process of the universe self-reproduction.

Thus during the last ten years inflationary theory changed considerably. It has broken an umbilical cord connecting it with the old big bang theory, and acquired an independent life of its own. For the practical purposes of describing the observable part of our Universe one may still speak about the big bang, just as one can still use Newtonian gravity theory to describe the Solar system with very high precision. However, if one tries to understand the beginning of the Universe, or its end, or its global structure, then some of the notions of the big bang theory become inadequate. One of the main principles of the big bang theory is the homogeneity of the Universe. The assertion of homogeneity seemed to be so important that it was called “the cosmological principle.” Without using this principle it is hard to prove that the whole Universe appeared *at a single moment of time*, which was associated with the big bang. So far, inflation remains the only theory which explains why the observable part of the Universe is almost homogeneous. However, many versions of inflationary cosmology predict that on a much larger scale the Universe should be extremely inhomogeneous, with energy density varying from the Planck density to almost zero. This is a consequence of the self-reproduction of the universe which we just discussed. Instead of one single big bang producing a single-bubble universe, we are speaking now about inflationary bubbles producing new bubbles, producing new bubbles, *ad infinitum*. In the new theory there is no end of the universe evolution, and the notion of the big bang loses its dominant position, being removed to the indefinite past.

From this new perspective many old problems of cosmology, including the problem of initial conditions, look much less profound than they seemed before. In many versions of inflationary theory it can be shown that the fraction of the volume of the universe with given properties (with given values of fields, with a given density of matter, etc.) does not depend on time, both at the stage of inflation and even after it. Thus each part of the universe evolves in time, but the universe as a whole may be stationary, and the properties of its parts do not depend on the initial conditions [14].

Of course, this happens only for the (rather broad) set of initial conditions which lead to self-reproduction of the universe. However, only finite number of observers live in the universes created in a state with initial conditions which do not allow self-reproduction, whereas infinitely many observers live in the universes with the conditions which allow self-reproduction. Thus it seems plausible that we (if we are typical, and live in the place where most observers do) should live in the universe created in a state with initial conditions which allow self-reproduction. Incidentally, such initial conditions appear with a much greater probability if one uses the tunneling wave function of the universe [12] rather than the Hartle-Hawking one [13]. On the other hand, stationarity of the self-reproducing universe implies that an exact knowledge of these initial conditions in a self-reproducing universe is irrelevant for the investigation of its future evolution. In this sense the debate about the choice of the wave function describing initial conditions loses its importance. One may argue that even the models of chaotic inflation with the potentials which do not allow inflation near the Planck density (like the potentials used in new inflation) become acceptable as far as they can support self-reproduction of the universe [14].

During the process of self-reproduction, the universe becomes divided into exponentially large domains containing matter in all possible “phases” corresponding to all possible vacuum states of the theory. Investigation of the distribution of volume of different domains in the universe may give us a possibility to explain geometric properties of space (including its dimensionality and the type of compactification) and to find “most probable” values of coupling constants in our part of the universe [14, 15, 16]. This possibility, however, depends on the as-yet unsolved problem of measure in quantum cosmology.

3 Inflation with $\Omega \neq 1$

The new cosmological paradigm may have important implications not only for our understanding of the global structure and the fate of inflationary universe, but for observational cosmology as well. For example, until very recently it was believed that the universe after inflation must become extremely flat, with $\Omega = 1 \pm 10^{-4}$. If observational data will show that Ω differs from 1 by more than a fraction of a percent, most of inflationary models will be disproved.

Fortunately, it is possible to solve this problem, both for a closed universe and for an open one. The main idea is to use the well known fact that the region of space created in the process of a quantum tunneling tends to have a spherically symmetric shape, and homogeneous interior, if the tunneling probability is suppressed strongly enough. Then such bubbles of a new phase tend to evolve (expand) in a spherically symmetric fashion. Thus, if one could associate the whole visible

part of the universe with an interior of one such region, one would solve the homogeneity problem, and then all other problems will be solved by the subsequent relatively short stage of inflation.

For a closed universe the realization of this program is relatively straightforward [17]. One should consider the process of quantum creation of a closed inflationary universe from “nothing.” If the probability of such a process is exponentially suppressed (and this is indeed the case if inflation is possible only at the energy density much smaller than the Planck density [18]), then the universe created that way will be rather homogeneous from the very beginning.

The situation with an open universe is much more complicated. Indeed, an open universe is infinite, and it may seem impossible to create an infinite universe by a tunneling process. However, this is not the case: any bubble formed in the process of the false vacuum decay looks from inside like an infinite open universe [19]. If this universe continues inflating inside the bubble then we obtain an open inflationary universe.

There is an extensive investigation of the one-bubble open universe scenario. However, until very recently it was not quite clear whether it is possible to realize this scenario in a natural way. An important step in this direction was made when the first semi-realistic models of open inflation were proposed [20]. These models were based on chaotic inflation and tunneling in the theories of one scalar field ϕ . However, as was shown in [17], in the natural versions of such theories the tunneling occurs not by bubble formation, but by jumping onto the top of the potential barrier described by the Hawking-Moss instanton. This leads to formation of inhomogeneous domains of a new phase, and the whole scenario fails. In order to resolve this problem one is forced either to introduce very complicated effective potentials, or consider theories with nonminimal kinetic terms for the inflaton field. This makes the models fine-tuned and complicated. It was very tempting to find a more natural realization of the inflationary universe scenario which would give inflation with $\Omega < 1$.

Fortunately, this goal can be easily achieved if one considers models of two scalar fields [17]. One of these fields may be the standard inflaton field ϕ with a relatively small mass, another may be, e.g., the scalar field responsible for the symmetry breaking in GUTs. The presence of two scalar fields allows one to obtain the required bending of the inflaton potential by simply changing the definition of the inflaton field in the process of inflation. At the first stage the role of the inflaton is played by a heavy field with a steep barrier in its potential, while on the second stage the role of the inflaton is played by a light field, rolling in a flat direction “orthogonal” to the direction of quantum tunneling. Inflationary models of this type are quite simple, yet they have many interesting features. In these models the universe consists of infinitely many expanding bubbles immersed into exponentially expanding false vacuum state. Each of these bubbles inside looks like an infinitely large open universe, but the values of Ω in these universes may take any value from 1 to 0. Thus we are again describing a self-reproducing universe consisting of many (infinitely large) universes with different properties.

Here we will describe an extremely simple model of two scalar fields, where the universe after inflation becomes open in a very natural way. Consider a model of two noninteracting scalar fields, ϕ and σ , with the effective potential $V(\phi, \sigma) = \frac{m^2}{2}\phi^2 + V(\sigma)$. Here ϕ is a weakly interacting inflaton field, and σ , for example, can be the field responsible for the symmetry breaking in GUTs. We will assume that $V(\sigma)$ has a local minimum at $\sigma = 0$, and a global minimum at $\sigma_0 \neq 0$, just as

in the old inflationary theory. For definiteness, one may assume that this potential is given by $\frac{M^2}{2}\sigma^2 - \alpha M\sigma^3 + \frac{\lambda}{4}\sigma^4 + V(0)$, with $V(0) \sim \frac{M^4}{4\lambda}$, but it is not essential; no fine tuning of the shape of this potential is required. Inflation begins at $V(\phi, \sigma) \sim M_P^4$. At this stage fluctuations of both fields are very strong, and the universe enters the stage of self-reproduction, which finishes for the field ϕ only when it becomes smaller than $M_P\sqrt{\frac{M_P}{m}}$ and the energy density drops down to mM_P^3 . Quantum fluctuations of the field σ in some parts of the universe put it directly to the absolute minimum of $V(\sigma)$, but in some other parts the scalar field σ appears in the local minimum of $V(\sigma)$ at $\sigma = 0$.

The main idea of our scenario can be explained as follows. Because the fields σ and ϕ do not interact with each other, tunneling to the minimum of $V(\sigma)$ in different parts of the universe may occur at different values of the field ϕ . The parameters of the bubbles of the field σ are determined by the mass scale M corresponding to the effective potential $V(\sigma)$. This mass scale in our model is much greater than m . Thus the duration of tunneling in the Euclidean “time” is much smaller than m^{-1} . Therefore the field ϕ practically does not change its value during the tunneling. If the probability of decay at a given ϕ is small enough, then it does not destroy the whole vacuum state $\sigma = 0$; the bubbles of the new phase are produced all the way when the field ϕ rolls down to $\phi = 0$. In this process the universe becomes filled with (nonoverlapping) bubbles immersed in the false vacuum state with $\sigma = 0$. Interior of each of these bubbles represents an open universe. However, these bubbles contain *different* values of the field ϕ , depending on the value of this field at the moment when the bubble formation occurred. If the field ϕ inside a bubble is smaller than $3M_P$, then the universe inside this bubble will have a vanishingly small Ω , at the age 10^{10} years after the end of inflation it will be practically empty, and life of our type would not exist there. If the field ϕ is much greater than $3M_P$, the universe inside the bubble will be almost exactly flat, $\Omega = 1$, as in the simplest version of the chaotic inflation scenario. It is important, however, that *in an eternally existing self-reproducing universe there will be infinitely many universes containing any particular value of Ω , from $\Omega = 0$ to $\Omega = 1$* , and one does not need any fine tuning of the effective potential to obtain a universe with, say, $0.2 < \Omega < 0.3$.²

Should we take these models seriously? Should we admit that the standard prediction of inflationary theory that $\Omega = 1$ is not universally valid? I think that now it is too late to discuss this question: the genie is already out of the bottle. We know that inflationary models describing homogeneous inflationary universes with $\Omega \neq 1$ do exist, whether we like it or not. It is still true that the models which lead to $\Omega = 1$ are much more abundant and, arguably, more natural. However, in our opinion, it is very encouraging that inflationary theory is versatile enough to include models with all possible values of Ω .

This situation makes some observers unhappy. Few years ago it seemed that they can easily kill inflationary theory if they find that the density of the universe is not equal to the critical density. It would be a significant scientific result. Now the situation changed. If we find that $\Omega = 1$, it will be a confirmation of inflationary theory because 99% of inflationary models do predict that $\Omega = 1$, and no other theories make this prediction. On the other hand, if observations will show that $\Omega \neq 1$, it will not disprove inflation.

This does not make inflationary theory untestable. Indeed, each particular inflationary model can be tested and ruled out by comparison of its predictions with observational data. In particular,

²The theories of two scalar fields which allow a definite prediction for Ω are also possible [21].

the simplest model of open universe which I just described needs to be modified: in its original form it predicts too large anisotropy of the microwave background radiation [17, 22]. Fortunately, this problem disappears after a minor modification of the model [17]: $V(\phi, \sigma) = \frac{g^2}{2}\phi^2\sigma^2 + V(\sigma)$. Thus, comparison with observations may rule out many versions of inflationary theory which otherwise look rather attractive. However, it is very difficult to disprove the basic idea of inflation. But it is not our goal, is it?

To make my position more clear, I would like to discuss the history of the standard model of electroweak interactions [23]. Even though this model was developed by Glashow, Weinberg and Salam in the 60's, it became popular only in 1972, when it was realized that gauge theories with spontaneous symmetry breaking are renormalizable [24]. However, it was immediately pointed out that this model is far from being perfect. In particular, it was not based on the simple group of symmetries, and it had anomalies. Anomalies could destroy the renormalizability, and therefore it was necessary to invoke a mechanism of their cancellation by enlarging the fermion sector of the theory. This did not look very natural, and therefore Georgi and Glashow in 1972 suggested another model [25], which at the first glance looked much better. It was based on the simple group of symmetry $O(3)$, and it did not have any anomalies. In the beginning it seemed that this model is a sure winner. However, after the discovery of neutral currents which could not be described by the Georgi-Glashow model, everybody forgot about the issues of naturalness and simplicity and returned back to the more complicated Glashow-Weinberg-Salam model, which gradually became the standard model of electroweak interactions. This model has about twenty free parameters which so far did not find an adequate theoretical explanation. Some of these parameters may appear rather unnatural. The best example is the coupling constant of the electron to the Higgs field, which is 2×10^{-6} . It is a pretty unnatural number which is fine-tuned in such a way as to make the electron 2000 lighter than the proton. It is important, however, that all existing versions of the electroweak theory are based on two fundamental principles: gauge invariance and spontaneous symmetry breaking. As far as these principles hold, we can adjust our parameters and wait until they get their interpretation in a context of a more general theory. This is the standard way of development of the elementary particle physics.

For a long time cosmology developed in a somewhat different way, because of the scarcity of reliable observational data. Ten years ago many different cosmological models (HDM, CDM, $\Omega = 1$, $\Omega \ll 1$, etc.) could describe all observational data reasonably well. The main criterion for a good theory was its beauty and naturalness. Now it becomes increasingly complicated to explain all observational data. Therefore cosmology is gradually becoming a normal experimental science, where the results of observations play a more important role than the considerations of naturalness. However, in our search for a correct theory we cannot give up the requirement of its internal consistency. In particle physics the main principle which made this theory internally consistent was gauge invariance. It seems that in cosmology something like inflation is needed to make the universe large and homogeneous. It is true that most of the inflationary models predict a universe with $\Omega = 1$. Hopefully, several years later we will know that our universe is flat, which will be a strong experimental evidence in favor of inflationary cosmology in its simplest form. However, if observational data will show, beyond any reasonable doubt, that $\Omega \neq 1$, it will not imply that inflationary theory is wrong, just like the discovery of neutral currents did not disprove gauge theories of electroweak interactions. Indeed, the only consistent theory of a *large homogeneous* universe with $\Omega \neq 1$ which is available

now is based on inflationary cosmology.

Thus, by measuring Ω we may rule out a large class of inflationary models but we will be unable to rule out the idea of inflation. What's about microwave background anisotropy and the theory of large scale structure of the universe? Again, it is possible to confirm inflationary models because most of them predict perturbations with specific properties. However, if it so happens that inflationary perturbations are in a conflict with observational data, then one can easily propose inflationary models where inflation solves homogeneity, isotropy and other problems, but produces extremely small density perturbations. Then one will be free to use his best non-inflationary mechanism for production of density perturbations (strings, textures, etc.). They can be created, e.g., by nonthermal phase transitions after explosive reheating [27].

Perhaps there is a way to disprove inflationary cosmology by comparing its predictions with observational data: If we find that the universe rotates as a whole, or has any other anisotropy which is described by vector perturbations of metric, then it will be very difficult to make it compatible with inflation [26]. Indeed we know that scalar and tensor perturbations can be produced during inflation, but vector perturbations, just like other vector fields, can hardly be produced. But what if we find out a nontrivial way of producing vector perturbations, just like we found a way to produce an inflationary universe with $\Omega \neq 1$? It seems that the only sure way to kill inflationary cosmology (if one really wants to do it) is to suggest a better cosmological theory.

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